

Maine Fluorescent Lamp Study Final Report

Executive Summary:

In the year 2000, the Maine Legislature enacted a disposal ban on all mercury-added lamps following extensive debate focused on whether or not the ban should apply to lamps that pass the Toxicity Characteristic Leaching Procedure [TCLP]. The focus of this study was to determine total mercury content of certain common fluorescent lamps and whether or not lamps that are represented by manufacturers as TCLP-compliant¹ contain sufficiently lower amounts of mercury to warrant an exclusion from the enacted solid waste disposal ban. New and used lamps from ten popular lamp models were collected and tested for total mercury and TCLP mercury by specialized testing procedures. Results indicate that lamps that are represented as TCLP-compliant have total mercury results similar to their non-compliant counterparts. These results suggest that the disposal ban on all mercury-added lamps is appropriate.

Introduction:

In its 1997 annual report, Maine's Land & Water Resources Council recommended action to reduce mercury emissions by diverting mercury-added products from the solid waste stream. The Council subsequently prepared a report that identified specific mercury-added products and recommended a ban on their disposal in solid waste.

The Maine Legislature enacted the recommended disposal ban prospectively following extensive debate on whether or not the ban should apply to all fluorescent and other mercury-added lamps. Debate focused on whether or not the ban should apply to lamps that pass the TCLP. Under current state hazardous waste law, TCLP-compliant lamps can be placed in the solid waste stream; while non-compliant lamps, except those from households, must be recycled or sent to a hazardous waste disposal facility. This will change on July 15, 2002 when the new disposal ban takes effect for all mercury-added lamps except those generated by households. The ban is extended to households on January 1, 2005. The Department of Environmental Protection [ME DEP] is required to provide an assessment of the economic and environmental impacts of the ban as applied to TCLP-compliant lamps by January, 2002.

This study is part of the ME DEP required assessment of environmental impacts of the disposal ban. Analyses conducted under this study sought to provide data bearing on whether Maine should retain the full ban. The results were used to compare the mercury content of lamps represented as TCLP-compliant to lamps that are not represented as TCLP-compliant. "TCLP-compliant" means a lamp that is determined to be non-hazardous using the Toxicity Characteristic Leaching Procedure [TCLP]. In addition, the analyses were expected to yield accurate and reliable data bearing on the relevance and efficacy of the TCLP for measuring the environmental impacts of lamp disposal.

¹ Through out this paper, the designations "pass", "TCLP-pass", or "TCLP-compliant" refer to manufacturer representations of their products.

Study design was documented in the Fluorescent Lamp Study Quality Assurance Project Plan [QAPP], Revision 4, 3/20/2001 which was reviewed by stakeholders and approved by the Environmental Protection Agency-New England Region [EPA-NE].

Sampling:

Four foot fluorescent lamps from four different production batches for each of 10 lamp models were purchased, labeled, packed and shipped to the analytical laboratory according to the standard operating procedure [SOP] P1, which is included in appendix B of the Fluorescent Lamp Study QAPP. Sampling for this study was limited to lamps produced on or after January 1, 2000 in response to the National Electrical Manufacturers Association comment: *Lamps should all be of the same "vintage" i.e. manufactured in year 2000. With mercury reduction being such an active and ongoing issue, if the DEP purchases lamps from a variety of prior years, the results will be meaningless.*²

Used fluorescent lamps for the lamp models targeted in this study were provided by Northeast Lamp Recycling. Of the ten lamp models targeted, eight were available from Northeast Lamp Recycling; however, many of the used lamps available were produced prior to January 2000 which limits their usability for this study. "Used lamps" are defined as lamps disposed at the lamp recycling facility and thus were considered be representative of lamps that have entered the solid waste stream.

All lamps were shipped to the laboratory in special boxes provided by the Portland Office of the US Postal Service. A sampling audit was conducted during sampling/ packaging/ shipping activities and results of the audit are included in Attachment 1 of this report. ME DEP provided the analytical laboratory with a list of samples to be analyzed for the first round of testing. Additional samples were submitted for analysis based on statistical analysis of the validated results from the initial round according to procedures discussed in section 20 of the Fluorescent Lamp Study QAPP. Please refer to the **All** worksheet included in the Excel file [Lamp Results.xls] for a complete list of samples submitted for analysis.

Analysis:

To provide more representative sampling and avoid sub-sampling inconsistency, fluorescent lamps were analyzed on a "whole lamp" basis for TCLP mercury and total mercury according to laboratory standard operating procedures [SOP] included in Appendix D of the Fluorescent Lamp Study QAPP. TCLP and total mercury digestion methods are based on the Science Applications International Corporation study [Analytical Results of Mercury in Fluorescent Lamps, 1992]. TCLP protocols for sample preparation provided by National Electrical Manufacturers' Association [NEMA LL 1] were also incorporated into the TCLP SOP. All samples were analyzed by Hampton-Clark, Inc./ Veritech Laboratories in Fairfield, NJ. Prior to analysis of lamps, Performance Evaluation [PE] samples were analyzed and evaluated to assess laboratory capability. The TCLP PE indicated that the laboratory was proficient for this analysis. The total mercury PE indicated that the laboratory was experiencing some problem with the analytical protocol. The calibration protocol was revised as a result of the PE and a new

² In a 1992 study, EPA reported average total mercury levels in 4-foot lamps (25 lamps tested) as 33 mg/lamp for used lamps, and 29 mg/lamp for new lamps. EPA 1992, Management of Used Fluorescent Lamps: A Preliminary Risk Assessment, Table 1-3, pp 6-7

PE sample was analyzed successfully on 7/18/01. In addition, enough of the PE sample was sent to the laboratory to be analyzed as an independent standard reference material [SRM] with each batch of total mercury samples. For a full report of the PE and the associated revision in calibration protocol, see Attachment 2 of this report. SRM results for each analytical batch are included on the **SRM** worksheet in the attached Excel file [Lamp Results.xls] and are summarized in the **Data Usability** section of this report.

Data Validation:

Data validation was completed by Kestrel Environmental Technologies, Inc. of Freeport, ME. A full tier III validation procedure according to Region 1, EPA-NE Functional Guidelines for Data Validation was performed. Full data validation reports are included in Attachment 3 of this report. A summary of these reports is given below.

Based upon the available information, all mercury results are reported without qualification for all sample delivery groups [SDG] with the exception of TCLP SDG 4. Results for TCLP SDG 4 were qualified with a "J" [estimated] because matrix spike recoveries were outside [low] Region 1, EPA-NE Functional Guidelines for Data Validation criteria indicating that sample results may be biased low. However, matrix spike recoveries were within QAPP measurement performance criteria [MPC] for these samples and were therefore deemed usable for purposes of this study. Of the fourteen used lamps analyzed in TCLP SDG 4, two were for lamp model GE 13803, four for Sylvania 24596, four for Sylvania 21824, and four for Sylvania 24594. Only four samples in SDG 4 had results below the TCLP limit of 0.2 mg/L, and those were all Sylvania 24596, which are classified as TCLP-compliant by manufacturer testing.

Sample Results:

TCLP results generally confirmed manufacturer designations for TCLP-compliant [Pass] versus non TCLP-compliant [Fail] lamps; however TCLP results for new lamps are expected to be significantly lower than results for lamps at the end of life.³ Used lamps for two lamp models [GE 26668 & Sylvania 21999] were not available for testing, and lamps from several other models were produced before January 2000 as noted in the result summary table *TCLP Mercury Results for Used Lamps*. Used lamps produced after January 1, 2000 appear to either have failed prematurely or have been recycled prior to lamp failure since the average life expectancy of these lamps is 20,000 hours. New lamps for one lamp model [GE 15949] in the "T8-Fail" classification did pass TCLP, however used lamps for the same model failed the TCLP. Full results are included on the **TCLP-New** and **TCLP-Used** worksheets in the attached Excel file [Lamp Results.xls]. Summaries of results are included in the following tables.

³ Lamps are dosed with elemental mercury when manufactured, and new, un-used lamps would be expected to exclusively contain this form of mercury. When lamps are burned, some portion of the elemental mercury initially present is converted to mercury salts (amounts and type depend on lamp design, including type of phosphor used, and hours burned before discarded), including oxides, which are more soluble in weak acids and acetate than elemental mercury. See Hildenbrand, et al., 2000, Interactions of thin oxide films with a low-pressure mercury discharge, Thin Solid Films 371 (2000) 295-302; and CRC Handbook of Chemistry and Physics, 82nd Edition, 2001

TCLP Mercury Results for New Lamps

MFG	Lamp Model	Class ¹	Average TCLP mg/L ²	# samples required ³	# samples analyzed	# Lamps from Y2K ⁴
GE	13803	T12 Fail	0.264	6	8	8
Sylvania	24594	T12 Fail	0.395	1	4	4
GE	23010	T12 Pass	0.16	1	4	4
Philips	24470-7	T12 Pass	0.089	1	4	4
Sylvania	24596	T12 Pass	0.16	1	4	4
GE	15949	T8 Fail	0.147	4	4	4
Sylvania	21824	T8 Fail	0.413	1	4	4
GE	26668	T8 Pass	0.065	1	4	4
Philips	27248-4	T8 Pass	0.091	1	4	4
Sylvania	21999	T8 Pass	0.16	2	4	4

- 1 **Class** = Lamp size [T8 vs T12] and whether or not the manufacturer represents this lamp model as TCLP compliant.
- 2 The TCLP regulatory limit is 0.200 mg/L. Results above 0.200 mg/L fail TCLP.
- 3 **# samples required** = number of samples required to provide a representative sample as calculated according to EPA SW-846 Chapter 9 Table 9-1 formulas for standard TCLP hazardous waste determination.
- 4 **# Lamps from Y2K** represents the number of lamps manufactured in January 2000 or more recently, and was determined by comparing date codes printed on lamps to date code information supplied by the three manufacturers.

TCLP Mercury Results for Used Lamps

MFG	Lamp Model	Class ¹	Average TCLP mg/L ²	# samples required ³	# Lamps analyzed	# Lamps from Y2K ⁴
GE	13803	T12 Fail	0.363	4	4	1
Sylvania	24594	T12 Fail	0.563	1	4	0
GE	23010	T12 Pass	0.133	2	4	4
Philips	24470-7	T12 Pass	0.095	1	4	4
Sylvania	24596	T12 Pass	0.089	1	4	4
GE	15949	T8 Fail	0.548	2	4	0
Sylvania	21824	T8 Fail	0.703	5	4	0
GE	26668	T8 Pass	Not Available	NA	0	0
Philips	27248-4	T8 Pass	0.092	1	4	4
Sylvania	21999	T8 Pass	Not Available	NA	0	0

- 1 **Class** = Lamp size [T8 vs T12] and whether or not the manufacturer represents this lamp model as TCLP compliant.
- 2 The TCLP regulatory limit is 0.200 mg/L. Results above 0.200 mg/L fail TCLP.
- 3 **# samples required** = number of samples required to provide a representative sample as calculated according to EPA SW-846 Chapter 9 Table 9-1 formulas for standard TCLP hazardous waste determination.
- 4 **# Lamps from Y2K** represents the number of lamps manufactured in January 2000 or more recently, and was determined by comparing date codes printed on lamps to date code information supplied by the three manufacturers.

Total mercury average results for new lamp models were based on twenty samples [per model] submitted for analysis. Several models contained less than twenty results due to a laboratory error, which invalidates SDG-1 [see **Data Usability**]. Full results are included on the **THg New**

worksheet in the attached Excel file [Lamp Results.xls]. Summaries of results are included in the following tables.

Total Mercury Results for New Lamps Sorted by Lamp Model

MFG	Class ¹	Lamp Model	Average mg/Kg ²	Average mg/Lamp	Lower CI ³ mg/ Lamp	Upper CI ⁴ mg/ Lamp	% Error ⁵	# Lamps analyzed
GE	T12 Fail	13803	12.1	3.42	2.43	4.41	29.0	19
GE	T12 Pass	23010	13.7	3.89	3.07	4.71	21.2	20
GE	T8 Fail	15949	20.4	3.78	3.05	4.50	19.2	20
GE	T8 Pass	26668	12.6	2.35	1.76	2.94	25.0	20
Philips	T12 Pass	24470-7	8.7	2.33	1.93	2.72	16.9	17
Philips	T8 Pass	27248-4	12.1	2.31	1.98	2.63	14.0	16
Sylvania	T12 Fail	24594	12.4	3.44	2.34	4.54	31.9	20
Sylvania	T12 Pass	24596	11.4	3.19	2.62	3.75	17.7	16
Sylvania	T8 Fail	21824	36.4	6.00	4.49	7.50	25.1	16
Sylvania	T8 Pass	21999	21.1	3.68	2.91	4.46	21.0	16

- 1 **Class** = Lamp size [T8 vs T12] and whether or not the manufacturer represents this lamp model as TCLP compliant.
- 2 **Average mg/Kg** = This is a calculated PPM value based on results and lamp mass.
- 3 **Lower CI** = Lower Confidence Interval, determined according to EPA SW-846 Chapter 9 Table 9-1 formulas using double sided 95th percentile t-scores.
- 4 **Upper CI** = Upper Confidence Interval, determined according to EPA SW-846 Chapter 9 Table 9-1 formulas using double sided 95th percentile t-scores.
- 5 **% Error** = Error of the mean at the 95th percentile, determined according to EPA SW-846 Chapter 9 Table 9-1 formulas using double sided 95th percentile t-scores.

Another view of this data showing the comparison of TCLP-compliant [Pass] total mercury averages compared to their non-compliant [Fail] counterparts is presented and reviewed in the **Discussion** section of this report.

In the following table results are summarized by grouping all three lamp manufacturers together according to lamp size and TCLP status [Class]. These results are also reviewed in the **Discussion** section of this report.

Total Mercury Results For New Lamps Sorted by Lamp Class

Class ¹	Average mg/Kg ²	Average mg/Lamp	Lower CI ³ mg/Lamp	Upper CI ⁴ mg/Lamp	% Error ⁵	# Lamps analyzed
T12 Fail	12.3	3.43	2.72	4.14	20.7	39
T12 Pass	11.4	3.18	2.78	3.57	12.5	53
T8 Fail	27.5	4.76	3.94	5.59	17.4	36
T8 Pass	15.0	2.75	2.38	3.11	13.2	52

- 1 **Class** = Lamp size [T8 vs T12] and whether or not the manufacturer represents this lamp model as TCLP compliant.
- 2 **Average mg/Kg** = This is a calculated PPM value based on results and lamp mass.
- 3 **Lower CI** = Lower Confidence Interval, determined from formulas based on SW-846 Chapter 9 Table 9-1 using double sided 95th percentile t-scores.
- 4 **Upper CI** = Upper Confidence Interval, determined from formulas based on SW-846 Chapter 9 Table 9-1 using double sided 95th percentile t-scores.
- 5 **% Error** = Error of the mean at the 95th percentile, determined from formulas based on SW-846 Chapter 9 Table 9-1 using double sided 95th percentile t-scores.

The number of total mercury tests performed on used lamps is limited due to the lack of availability of newer models at the recycling facility (presumably most lamps manufactured after 1/1/2000 are still in service). Results were based on two to five samples for each of the eight available lamp models. Many of the used lamps were manufactured prior to January 2000. Lamps manufactured in years prior to January 2000 were produced with a variety of mercury dosing concentrations. Because only a limited number of samples were analyzed and many of these were from different production years, it is not appropriate to compare average results as done above for the new lamps. Full results for the twenty-six samples analyzed, including production dates, are recorded on the **THg Used** worksheet in the Excel file [Lamp Results.xls].

Data Usability:

All validated data were evaluated and reconciled with project quality objectives according to procedures in the Fluorescent Lamp Study QAPP, section 20.

TCLP testing was conducted in order to confirm manufacturers' TCLP rating for the lamps evaluated in this study. Results for new lamp TCLP testing meet the requirements of the QAPP. In each case enough samples were analyzed to characterize the lamps as either TCLP-compliant [Pass] or non-compliant [Fail]. However, since TCLP results increase as lamps age, it is important to also run TCLP on lamps at the end of life. Since industry has lowered mercury dosing of lamps in recent years, our study focussed on newer lamp models for which spent lamps were not commonly available.

Results for total mercury analyses do not meet the QAPP requirement that the mean be determined with an accuracy of $\pm 10\%$ at the 95th percentile. Initial calculations indicated that more than 20 samples of each model would need to be tested to meet this objective. In some cases several hundred samples would need to be analyzed to meet the objective. The alternative objective is to calculate the error of the mean at the 95th percentile for the lamps analyzed. This calculation is included in the above result summaries for new lamps. In addition, variability in the SRM sample was calculated to give some indication whether the analytical method is too variable to meet the QAPP requirement or whether results reflect the true variability in mercury dosing of lamps. SRM results for SDG 2 through SDG 12 [a total of 22 samples] were averaged and error of the mean at the 95th percentile determined. The true value for the SRM is 3.0 mg per sample, which is in the same concentration range of the lamps analyzed. The resulting statistics for the SRM are presented below:

SRM Statistics:	Result:
Average [mg/sample]	3.03
Lower CI [mg/sample]	2.94
Upper CI [mg/sample]	3.11
Error of the mean	2.85 %

These results indicate that the method variability for the SRM is well within the project requirement. The SRM matrix is water, which is not subject to the same digestion challenges as lamp samples; however, it does demonstrate that any error contributions from the determinative portion of the analysis and error associated with dilution procedures are low. Additional testing

would be required to determine whether the digestion method for whole lamp analysis significantly contributed to the variability of the results.

It is also possible that the amount of mercury recovered from lamps is less than 100% recovery because of matrix problems. Because each lamp was totally consumed in the testing process it was not possible to assess matrix problems with the customary matrix spike. Quality Control information obtained from Philips Lighting for T8 lamp model 27248-4 from the four production dates for lamps included in this study are tabled below:

Production Date	Philips weight average ¹ [mg/Lamp]	Study Average [mg/Lamp]	Percent Recovery ²
September 2000	3.52	2.50	71.0
November 2000	3.52	2.20	62.5
December 2000	3.51	2.58	73.5
January 2001	3.53	1.95	55.2
total	3.52	2.31	65.6

1. Philips weight average = The average weight of mercury used to dose Philips lamp model 27248-4 based on a sampling of 6 to 8 mercury dosing capsules for each production batch.
2. Percent Recovery = Study Average/Philips weight average X 100%, and assumes that the Philips weight average is the correct lamp mercury dose.

These results indicate that the recovery of mercury from lamps in the total mercury test may be only 65.6% of the total lamp mercury content. Although percent recovery of total mercury is likely to be biased low, it is generally assumed that all lamps will be affected more or less equally, and that comparisons among lamp manufacturers and lamp classes are valid.

To answer the question as to what extent the analytical digestion method used in this study contributes to bias and variation in analytical results a follow-up study will be done. In the follow-up study 20 undosed lamps will be spiked with known amounts of mercury in the laboratory. The 20 spiked lamps, along with 2 undosed lamps [matrix blanks] will be digested and analyzed at the same laboratory according to the same standard operating procedures [SOP] followed in the original study. The resulting average % recovery, confidence intervals, and error of the mean will be compared to the SRM and lamp results from the original study.

A review of validated data for total mercury revealed that results from SDG 1 gave generally higher results than other total mercury sample delivery groups. Results from SDG 1 are compared to results from subsequent SDG in the following table:

MFG	Class ¹	Lamp Model	SDG 1 Average mg/Lamp	Subsequent SDG Average mg/Lamp
Philips	T12 Pass	24470-7	4.50	2.33
Philips	T8 Pass	27248-4	6.33	2.31
Sylvania	T12 Pass	24596	6.85	3.19
Sylvania	T8 Fail	21824	15.2	6.00
Sylvania	T8 Pass	21999	12.0	3.68

- 1 **Class** = Lamp size [T8 vs T12] and whether or not the manufacturer represents this lamp model as TCLP compliant.

When lamps of the same model were compared across sample delivery groups it appeared that something had changed in the analytical realm. The laboratory was contacted, and it was discovered that the reagent blank water that was used when making dilutions had been changed after SDG 1. For SDG 1 de-ionized water was used for dilutions. In subsequent SDG reagent blank water for dilutions contained acid at the same concentration as the samples. The standard operating procedure for dilutions is to use reagent blank water containing acid at the same concentration as the samples. For this reason results from SDG 1 were removed from data summaries included in this report. An analysis of this problem by Veritech Laboratory is included in the Lamp Study records.

Discussion:

In this study TCLP testing was performed to confirm manufacturer representations of TCLP status for lamps evaluated in this study. Total mercury results for these lamps were then evaluated to determine whether the TCLP test is useful to determine environmental impacts from lamps based on their total mercury content. It should be noted that the TCLP was intended to be a measure of the leachability of mercury from a waste, not an indicator of total mercury content or of total environmental impact. It will only be a measure of potential ground water contamination and water transport of mercury contamination. Since environmental impacts of mercury may include other pathways, for example mercury vapor in landfill gas, the total mercury content of lamps may be a better indicator of environmental impact. However, there has been a perception that new TCLP-compliant lamps pass TCLP chiefly because the mercury content of these lamps has been significantly reduced.

When the average results for new lamps sorted by manufacturer and size are compared [Total Mercury Results Comparison Chart 1], the following observations apply. TCLP-compliant T8 lamps from GE and Sylvania appear to have lower total mercury content than their non-compliant counterparts. However, total mercury results for TCLP-compliant T12 lamps from GE and Sylvania do not appear to differ significantly from their non-compliant counterparts. Results for Philips were not compared because non-compliant models were not available.

Total Mercury Results Comparison Chart 1:

Lamp Size	Mfg	TCLP Compliant model [mg/Lamp] ¹	Non-compliant model [mg/Lamp] ²
T8	GE	2.35	3.78
T8	Sylvania	3.68	6.00
T12	GE	3.89	3.42
T12	Sylvania	3.19	3.44

1. TCLP Compliant model means that the lamp manufacturer represents these as lamps that pass TCLP limits for mercury.
2. Non-compliant model indicates that the manufacturer does not represent these as lamps that pass TCLP limits for mercury.

When lamp results are sorted and averaged by lamp size [Total Mercury Results Comparison Chart 2] TCLP compliant T8 lamps appear to contain less mercury than their non-compliant counterparts. However, T12 lamps do not appear to differ significantly based on TCLP compliance.

Total Mercury Results Comparison Chart 2:

Lamp Size	TCLP Compliant model [mg/Lamp] ¹	Non-compliant model [mg/Lamp] ²
T8	2.75	4.76
T12	3.18	3.43

1. TCLP Compliant model means that the lamp manufacturer represents these as lamps that pass TCLP limits for mercury.
2. Non-compliant model indicates that the manufacturer does not represent these as lamps that pass TCLP limits for mercury.

These results suggest that the TCLP test is not always effective in differentiating lamps based on their total mercury content. In other words, TCLP-compliant lamps may not have lower total mercury content than non-compliant lamps.

Twenty-six used lamps, representing eight of the ten target lamp models, were analyzed for total mercury in this study. However, results for used lamps were not combined with results for new lamps because fifteen of the twenty-six used lamps tested were manufactured prior to January, 2000 and would not be comparable in mercury dosing to the new lamps analyzed. Also, the analytical method for total mercury did not include a digestion capable of recovering mercury that may become imbedded in the glass during normal lamp use, a phenomenon that has been reported by lamp manufacturers. Results from the used lamps are documented on the **THg Used** worksheet of the Excel file [Lamp Results.xls] and were useful in a limited evaluation of how mercury content of lamps has been reduced since 1994.

Conclusions:

Based on the results of a statistically valid number of new lamps, the TCLP status of the ten lamp models was verified; however, sufficient numbers of used lamps were unavailable to confirm TCLP status.⁴

Based on the results of 180 new lamps and 26 used lamps tested for total mercury, two conclusions can be drawn. The TCLP is not a reliable test to differentiate lamps with higher total mercury content from those with lower total mercury content. It appears that lamps that are represented as TCLP-compliant do not have significantly lower mercury content from non-compliant lamps. Also, from a review of limited data on used lamps, recently manufactured lamps appear to contain less total mercury than their counterparts produced in earlier years.

The question as to what extent the analytical digestion method used in this study contributes to bias and variability in analytical results will be determined in a follow-up study.

⁴ Under RCRA regulations, waste generators are responsible for determining whether their wastes are hazardous (40 CFR 262.11). Since the form of mercury in lamps changes as lamps are burned, and since discarded lamps are typically used, not new lamps, data from TCLP testing of new lamps cannot be reliably used to determine the waste status of used, discarded lamps.